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Fluid Dynamic Aspects of Jet Noise Generation

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Dr. Sergio Panunzio

Dr. Simon Slutsky

Dr. Antonio Ferri
Director

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Introduction

The main objective of this experimental investigation is to obtain qualitative and quantitative information on the propagation of wave inside a jet (single or multiple) with particular attention to refraction of ray trajectories and distortion of wave profile due to nonlinear effects.

As shown in Ref. 1, the sound rays can originate in the disturbances of the mixing zone, (Fig. 1), propagate through the wake of the nozzle trailing edge, and enter into the supersonic part of the jet. Then after propagating downstream and crossing the sonic surface (M=1), they can curve back upstream and reinforce the original mixing zone disturbance. The focusing of sound rays on the axis together with the steepening of the compression wave front due to non-linear effects (that appear when high level of pressure fluctuation occurs inside the jet and propagate through the supersonic flow) can play an important role in creating zones of sound intensification or generation, particularly near the sonic surface (Fig.2) (Ref. 2.).

An experimental method is used in studying this phenomenon which consists of injecting from outside the jet, at one or various points near the mixing zone, a set of pressure signals, and detecting them with one or more microphones placed inside the jet. The signals are detected in the presence of the background noise of the jet itself, and the change of propagation time and form occuring at

various positions of the source-microphone set is being studied.

The development of this technique required the solution of many detailed problems. In particular, the intensity of the injected signal must be high enough to permit separation of the signal itself from the noise background; moreover, its initial form must not be steep if steepening due to travel inside the jet is to be studied.

The task of implementing the facility and the instrumentation was divided into three phases:

a. construction of the facility providing two concentric jets of cold air; calibration of the jet's aerodynamic characteristics and measurement of noise generated in the far field and near field for evaluation of uniformity, intensity, spectrum composition.

b. construction of a noise generator providing a set of one to six signals of appropriate intensity, frequency and form; channeling of the signals to the desired injection points, establishment of the signal form at the injection points, time-delay control are studied in this phase.

c. data acquisition system consisting of the microphone, the stand and scanning mechanism for the microphones and other probes, the recording system and signal enhancement system

for separation of the signal from the background noise of the jets; study of the controlling parameters to optimise the system.

State of the Work Performed to Date

In the Progress Report covering the period from September 1, 1972 through February 28, 1973, the facility was described in its more general configuration and for the specific study of two coaxial jets (cold air T_o=530 R) which were selected for this investigation, (Fig. 3).

The inner nozzle, with an exit section of 7" diameter, provides a M=2 supersonic jet, and requires 115 psia stagnation pressure to produce a jet with 14.7 psia static pressure, free of shock-expansion surfaces (mass flow 60 lbm/sec).

The outer nozzle provides, in the last configuration, an annular jet of 10" O.D. and 7" I.D. at M=1 also balanced, (Fig. 4), (P=30 psia, p=14.7 psia, 20 lbm/sec). The outer nozzle was designed initially for subsonic Mach Numbers with a jet exit O.D.=12"(also with a mass flow of 20 lbm/sec,) and tests of its characteristics, alone or together with the M=2 inner jet, have been performed. This set of nozzles was implemented with a series of pressure taps and tested to verify the flow axial symmetry and the Mach numbers obtained by using standard recording equipment.

On the other hand, since in this investigation we want to support a measuring probe (microphone, pitot, hot wire) inside the jet itself, a stand with sufficient strength and stiffness (Fig. 5) was prepared and implemented with an actuating mechanism (Fig. 6).

This permits scanning of the probe during the test over a displacement of 13", in a transversal direction with respect to the jet axis. In addition, the position of the stand can be varied up to 110" from the jet exit axially and 24" transversally by clamping it to a strong horizontal base.

A series of tests was conducted with various combinations of the jets mass flows, to measure: a) sound level in the far field at selected points; namely, at 46ft., 92 ft, distance and about 600 ft. across the Harlem River, at various angles with the jets axis; and b) pressure fluctuation level inside the jets. (tables 1 and 2)

Two noise generators have been prepared for this investigation. The first one, outlined in the last progress report, is a pneumatic system shown in Fig. 7 and consists of a manifold receiving air from the high pressure line (2000 psig) reduced to 20-200 psig by a pressure control valve. The air flow from the manifold enters into six 5/8" I.D. nozzles and is alternately shut off and opened by a rotating valve, (Fig. 8). This rotating valve is formed by a disc attached to an electric motor with speed variable up to 10,000 rpm, and presents in front of the nozzles a row of 24 circular windows of 1/2" diam. From the other side of the rotating disc, six pipes 5/8" I.D., placed in continuation of the six nozzles, bring the resulting pressure disturbances to the signal injection points.

The six lines are symmetrically placed around the axis of the tunnel and have the same length (about 10 feet), except for a U-shaped segment that permits one to change the line length about 1 foot, thereby introducing a delay-time in the signal arrival at the injection point of about 1.2 msec.

Experiments have been carried on one line only with disc speed of 2000 rpm, giving a signal frequency of 800 c/sec, using air pressure of 35 psia. Duct lengths of 1 foot and 10 feet were used. The signal intensity of 144 dB measured as peak to peak pressure level fluctuation, was obtained at 4 inches from the pipe outlet, with both pipe lengths. However, as expected, steepening of the signal profile occurs with the long pipe, in which case, the signals arrive as a series of spikes (Fig. 9). Since signals with small slopes are required, an additional device has been studied to regenerate a signal under excitement from the spike. Several configurations of Helmholtz resonators have been considered; the best results were obtained with the one shown in Fig. 11, and the signal produced is shown in Fig. 10.

This signal will be tested for its propagation through the jet as soon as the system will be available; however, it appeared convenient to use also an electrically driven system which provides a higher frequency range and a well-behaved signal form at all frequencies.

An Altec Lansing 100-watt driver has been tested for this purpose. This driver has a 1" dia. diaphragm, placed as near as possible to the sound injection points with a short 3" long catenoidal horn to optimize coupling of the driver with the external field.

Pure sinusoidal signals can be obtained up to 14 KHz, and intensity up to 154 dB at the throat at a frequency of 5 KHz.

Signal Processing and Instrumentation Problems

The success of the present jet noise program depends on our ability to note the development and nonlinear steepening of an externally injected signal as it propagates into and through the jet. Thus, current plans consist of the completion of the jet aerodynamic facility, construction of a set of high intensity, high repetition rate acoustic wave pulses, and investigation of the adequacy of the instrumentation and of data processing techniques.

An electronic simulation of the physical model has been carried out in order to check the adequacy of the sound wave source and of the operating procedures. An important result of this simulation was a better understanding of the very strong operational interdependence and limitations existing between signal amplitude, signal pulse repetition rate and total facility running time. The experimental set up of this simulation is outlined in Fig. 12.

The basic noise signal used was a triangular ramp with a duration of about .3 msec and a repetition rate of .6 msec (1600 pulses per second). Due to the use of a 10 KC low pass filter, considerable rounding of the signal occurs, as shown in Fig. 13, trace 1a. When the signal is mixed with white noise in the ration of 1 to 64, and then passed through the 10 KC low pass filter, the

signal to noise ratio is improved by a factor of about 2. The resulting mixed signal is shown is Fig. 13, trace 2a, and the pulse is apparently not detectable in the noise. When the signal is summed about 16,000 time using clipped mode summation, a signal can be detected, as in Fig. 13, trace 1b. The improvement in signal to noise is closely equal to the square root of the number of sums; i.e., 16,000=130 or 42 dB.

When the number of summations is increased to 32K, 64K and to the maximum storage capacity of the SAICOR SAI 42, the resultant detected signals improve as shown in Fig. 13, traces 3b, 3a and 2b, respectively,. Use of ordinary unclipped signals requires a much larger number of summations to achieve equivalent results. (Clipping is appropriate when the deterministic signal is a perturbation on the noise, but grossly distorts the detected result when the signal is comparable with the noise.)

For larger values of signal to noise ratios than those discussed above, the data processing is improved. In order to simulate this condition, the signal and noise were mixed in the ratios of 1/32, 1/16 and 1/8, and the detected signal improvements (at a constant 16K summations) are noted in Fig. 13, traces 4a, 4b and 5a, respectively, The combination of S/N=1/8 and 8K summations, gives the result noted Fig. 13 trace 5b, and is of the same quality as 4b and 5a.

In the above tests, the filter setting was chosen so that the pulse peak amplitude was not appreciably affected, while filtering out as much of the higher frequency noise as possible. The logic of this procedure must be further considered in the light of the following factors:

a. We lose details of the pulse rise shape if the pulse is steep fronted.

b. If the noise spectrum drops with frequency, then low pass filtering may be without benefit.

Since the amplitude of the classical jet noise spectrum drops at about 6 dB per octave at frequencies above the Strouhal frequency, our noise might be better represented by electronic "pink" noise than by "white". On the other hand, there are regions in the jet--the early stages of the mixing region--where the transition frequency is high, and so low pass filtering may be useful.

Simulation of the jet noise by electronic pink noise and subsequent processing, as discussed above for white noise, confirmed that use of the 10KC filter gave negligible increase in S/N ratio.

On the other hand, some improvement of S/N ratio was achieved (about 1.3) by filtering out the low frequency noise below 100 Hz. This filter setting permitted retention of the pulse rise detail, but produced some distortion in the flat portions.

An examination was made of the optimum procedure for operation of the Honeywell 5600 tape recorder in these tests. We may consider a choice from among the following options: a) operation in the FM "standard" mode which has a low pass cut off frequency at 60 ips of 10 KHz and a S/N ratio of 46 dB; b) "double extended" mode with low pass cut off frequency of 40 KHz and S/N ratio of 42 dB, and c) the "extended" mode with intermediate noise and cut off characteristics. Direct record modes are noisier and appear to be less advantageous. The tradeoff parameters considered in the above are similar to those involved in the filter choice; e.g., signal shape details versus noise, and consequent data running time. When 10 Kc low pass filtering is used, the specific recorder mode used becomes non-critical and a lower FM speed, such as 15 ips, is also useful.

The final choice of instrumentation parameters can be put off until after the systematic measurements of static pressure fluctuation amplitude and spectra are carried out in the jet core, secondary flow and mixing regions.

The effect of the microphone housing on the measured noise was also considered. Tangent ogive nose cones are being used with all pressure tansducers in these tests in order to respond to static pressure fluctuations only, and not to total pressure fluctuations, which would result in very large noise amplitudes. Kulite pressure

transducers are being employed within the jet in order to guard against possible damage from large total pressure fluctuations.

In conclusion, the above simulation study has allowed us to pinpoint the critical parameters which must be considered in the physical jet noise data acquisition program. The design of the shock pulse generator was modified to increase both pulse repetition rate and signal intensity, and the possible need of collecting data over several runs was noted.

Preliminary Tests on Noise Detection

During the final days of this progress period, a preliminary test of the ambient turbulent pressure fluctuation level was carried out. Initially a 1/2" diameter Statham pressure transducer was used and finally, we employed a new Kulite transducer of 1/4" O.D. and .08" diameter diaphragm. This transducer has a natural frequency of about 130 KHz and a maximum safe pressure range of 200 psi. The transducer was fitted with an ogival nose cone manufactured by Bruel and Kjaer. This transducer was chosen because the stagnation pressure in the nozzle flow is considerably in excess of the maximum allowed in the available B and K microphones.

Overall pressure fluctuation levels at the jet axis found in the primary flow during these preliminary tests varied between 160 and 170 dB. Since these flows were not run at design conditions, some variation of level may still be expected.

Preliminary tests were also made on the input pulse generator. These tests indicate that the input pulse amplitude as measured in still air at 1 foot from the generator exit, with maximum generator storage pressure is on the order of 150 dB.

At the time of this writing, preliminary results are being obtained, using the Alter-Lansing driver and driving with a 5000 Hz sinusoidal signal. Signals of fairly low amplitude, 138 dB at 4 inches from the horn exit are being detected at the centerline

of the Mach 2 jet. About 30 seconds of data were collected during this run. The results are considered crucial as well as extremely encouraging inasmuch as we expect soon to raise the input signal level by at least 10 dB. The subsequent steps of our program now appear to be realistic.

Conclusions and Programmed Subsequent Investigation

In this first part of the experimental investigation on noise propagation inside a jet, a facility has been implemented to provide two coaxial axisymmetric jets of unheated air. The large dimensions of the jets (7" dia. the inner one at M=2 and 10" dia. the outer one at M=1) is appropriate to permit one to place a set of microphones inside the jet core without disturbing significantly the jet flow and without affecting the noise generation and propagation. A 1/8" dia. microphone type Kulite=CQ-125, with a maximum signal pressure of 200 psia, is used considering the high stagnation pressure level (115 psi) and has been tested for sensitivity to static and stagnation pressure fluctuation.

It has been tested for both conditions using a 1/4" Bruel and Kjaer nose cone for static pressure pick-up and a specially constructed nose cone for stagnation pressure pick-up. An additional blind nose cone has been constructed and used in a test performed with the object to ascertain that the noise transmitted through ways other than air pressure fluctuation over the microphone is of sufficiently small level.

In this first part of the program no special care was taken to minimize the jet noise produced upstream at the nozzles. This will be done after completion of the tests in the actual configuration.

Noise levels of 170 dB for static pressure fluctuation have been measured at the jet axis. Preliminary estimates of the stagnation pressure fluctuation are of the order of 185 dB and indicate that the microphone was not overloaded.

A strong and rigid support of the microphone with a motorized supporting arm have been constructed permitting scanning of the jet, during the test, over 13 in. with a scanning speed of 1 in/sec. and has been tested for performance.

Two noise generators have been implemented, the first pneumatic and the second electric.

The first one will produce 6 pulsating pressure signals that will be injected at the jet boundary near the jet exit.

One signal only has been produced so far and analyzed for quality at 800 HZ frequency obtaining a noise intensity of 138 dB at 4 in. from the exit horn. The second noise generator produces a continuous sinusoidal signal at 5000 HZ with also 138 dB intensity at 4 in. from the exit ; it has been used in a typical test configuration and received by a microphone placed at the jet axis. The signal received was recorded on tape and analyzed with 1) a clipped mode enhancing system and 2) a cross correlation method. With both methods the signal was retrieved although estimated to be 44 dB below the jet noise level.

It is felt, therefore, that a systematic investigation program can be carried on in the future part of this study to trace the rays propagation inside the jets.

In the next part of the program the following steps will be covered:

a) The pneumatic noise generator will be brought to its final form and the level of the electric one increased to its maximum value.

b) A second microphone will be installed on the same stand parallel to the first at 1.1/2" distance with possibility to adjust and measure its axial position with respect to the first one. It will be used to measure the ray propagation direction using the time lag measured between the signals received by the two microphones.

c) A systematic test program will be conducted to trace the rays propagation from the source through the jet, in various configurations.

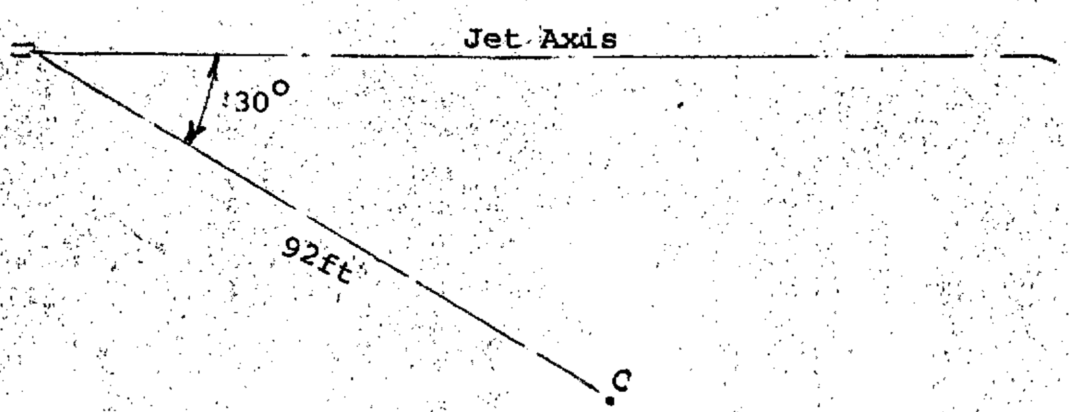
d) The plenum chamber of the primary jet will be modified by adding screening and a contraction cone to reduce the noise produced upstream of the nozzle.

By comparing tests on the <u>clean</u> versus the similar ones on the <u>noisy</u> jet configurations, valuable information will be obtained on the propagation inside the jet of noise introduced upstream of the nozzle.

References

Ref. 1 Supersonic Jet Engine Noise Analysis, A. Ferri, Lu Ting J. Werner, presented at Noise Symposium, Stamford University, Stamford, California--March 28-30, 1973

Ref. 2 Fluid Dynamic Aspects of Jet Noise Generation, A. Ferri, S. Slutsky, S. Panunzio, presented at Noise Symposium, Stamford University, Stamford, California--March 28-30, 1973



Noise Levels Due to Primary Jet To = 490°R

M exit	Pt	P exit	M	SPL at Point C
.95	36 psia	14.6 psia	19 lb/sec	109 dB linear
1.18	41 psia	17.2 psia	21 lb/sec	118 dB linear
1.99	79 psia	10.3 psia	41 lb/sec	122 dB linear
2.00	101 psia	12.9 psia	52 lb/sec	127 dB linear
2.00	1-7 psia	13.5 psia	55 lb/sec	128 db linear

Noise Level for Primary Jet of Various Stations

Table 1

Farfield Noise Measurements Primary Jet $T_o = 530^{\circ}R$

Distance	Angle From Centerline	Pt	SPL
600'	0°	107 psia	95 dBC
620'	15°	108 psia	104 dBC
850'	15°	107 psia	101 dBC
500'	30°	107 psia	100 dBC

Noise Level at More Than 600 ft. (across the Harlem River)

Table 2

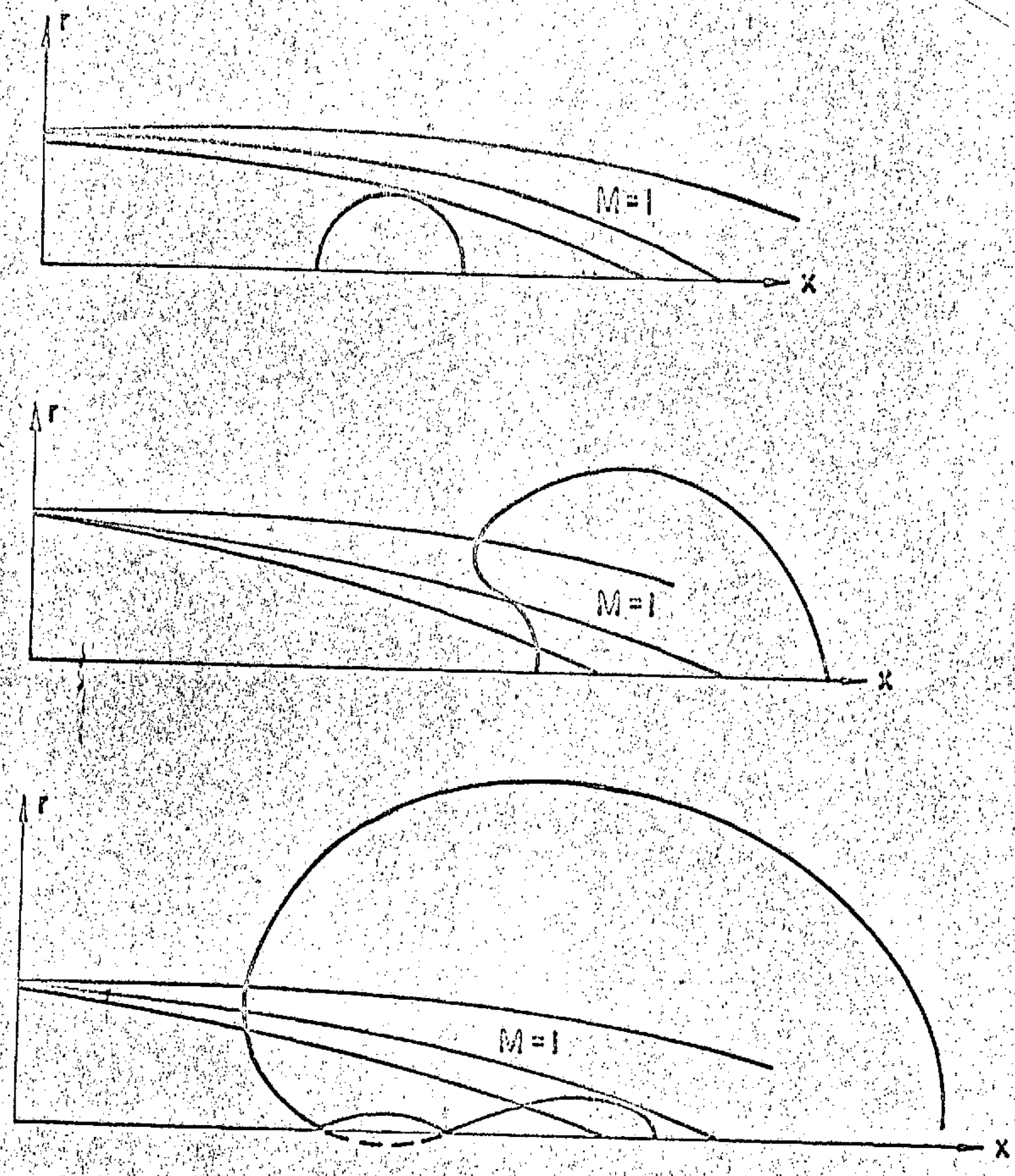


Fig. 1 Propagation of a pulse through the mixing zone

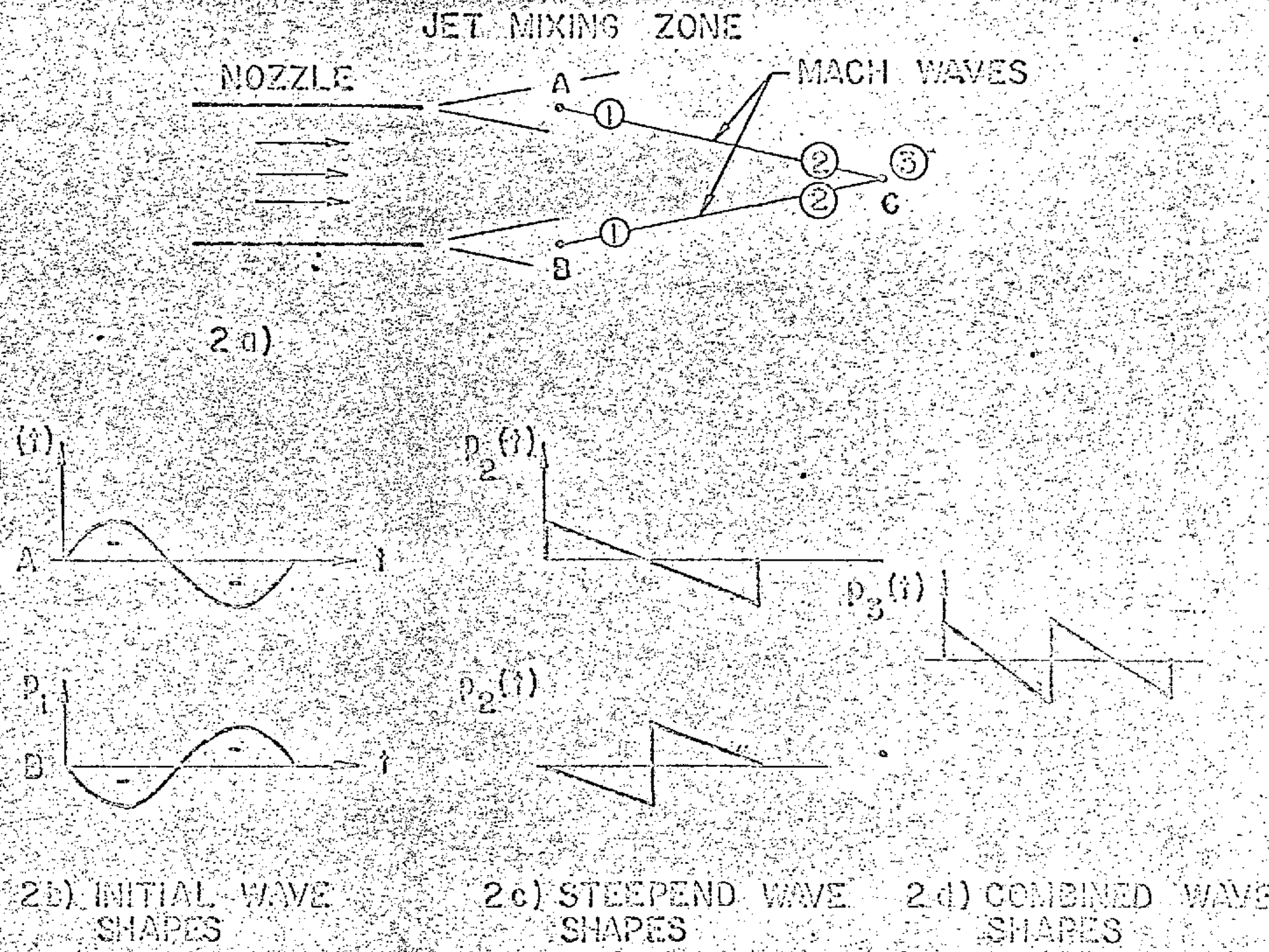


Fig. 2 Waves Focussing at the Jet Axis

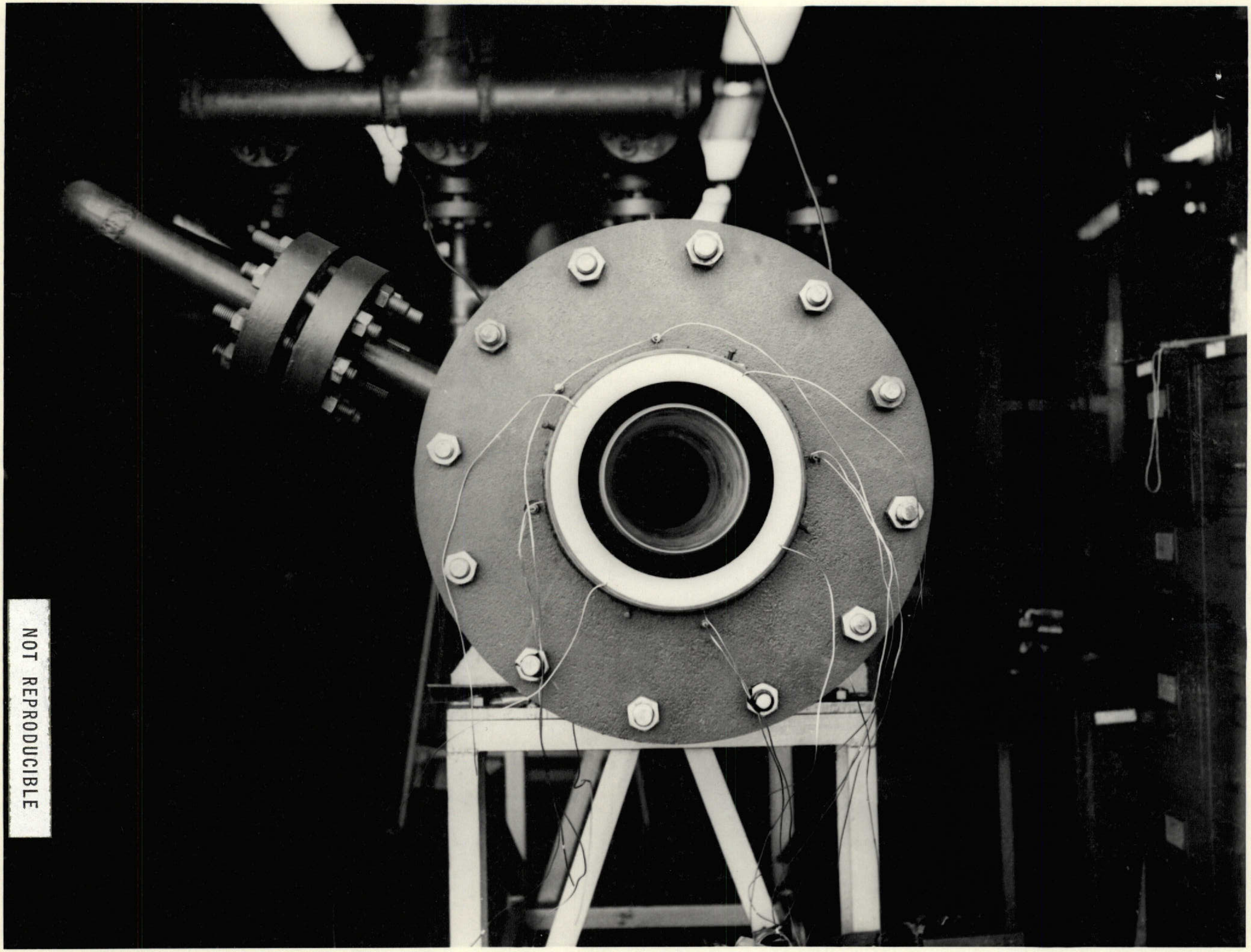


Fig. 3 Coaxial jets

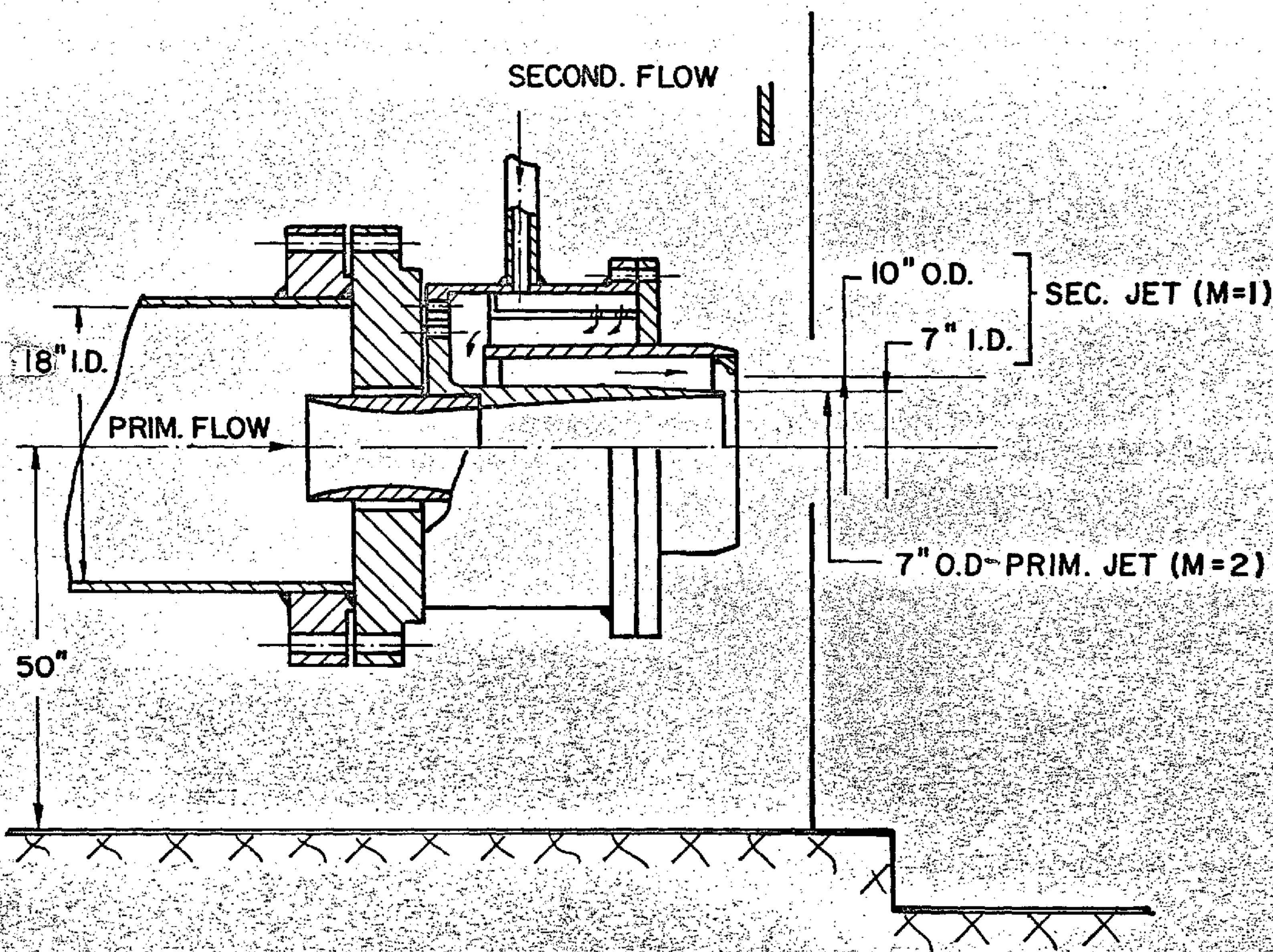


Fig. 4 Coaxial jets with modified outer (secondary) jet to M=1

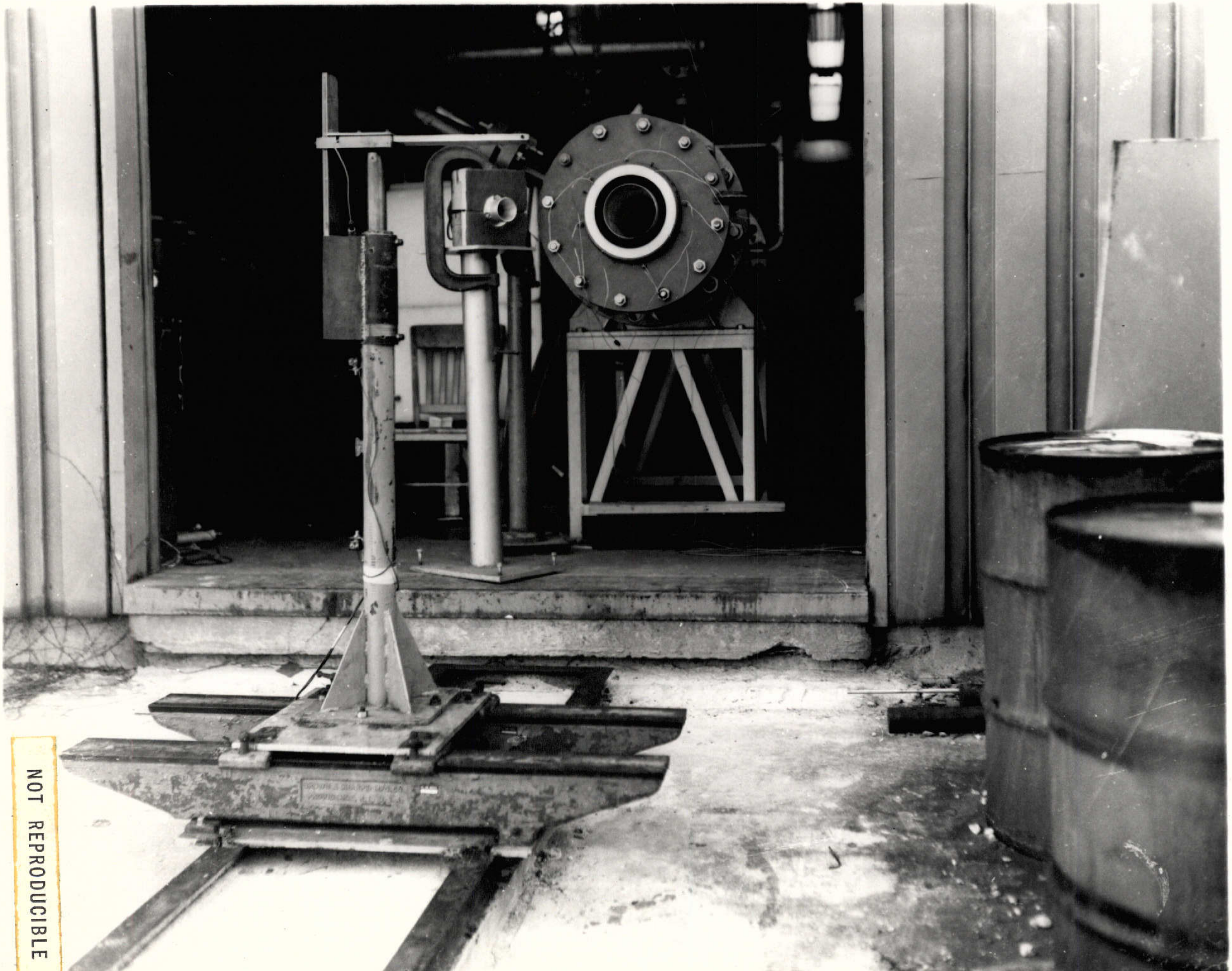


Fig. 5 Instrument stand. Experiemental set up shown with electric, Altec Lansing Driver

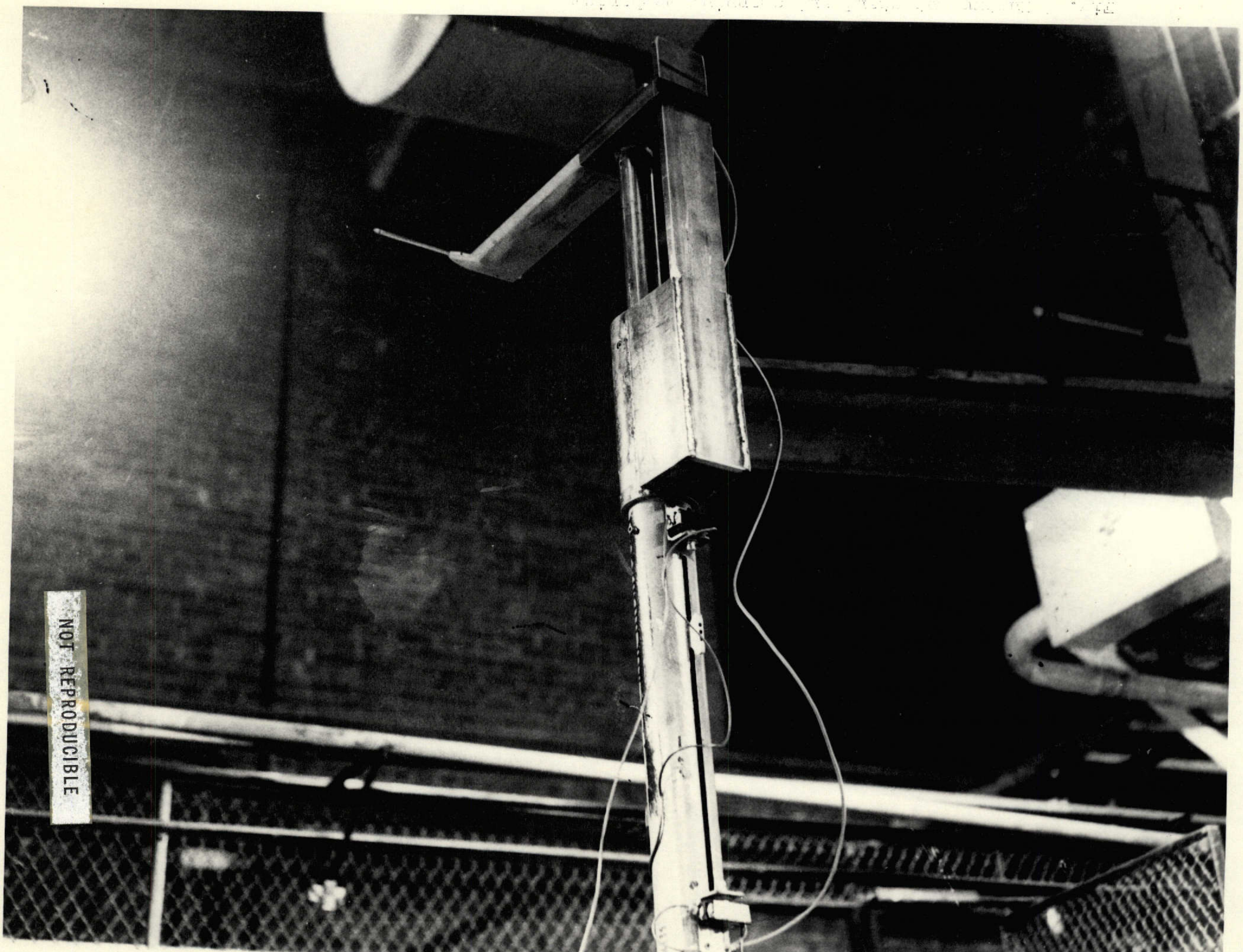


Fig. 6 Instrument stand and scanning mechanism

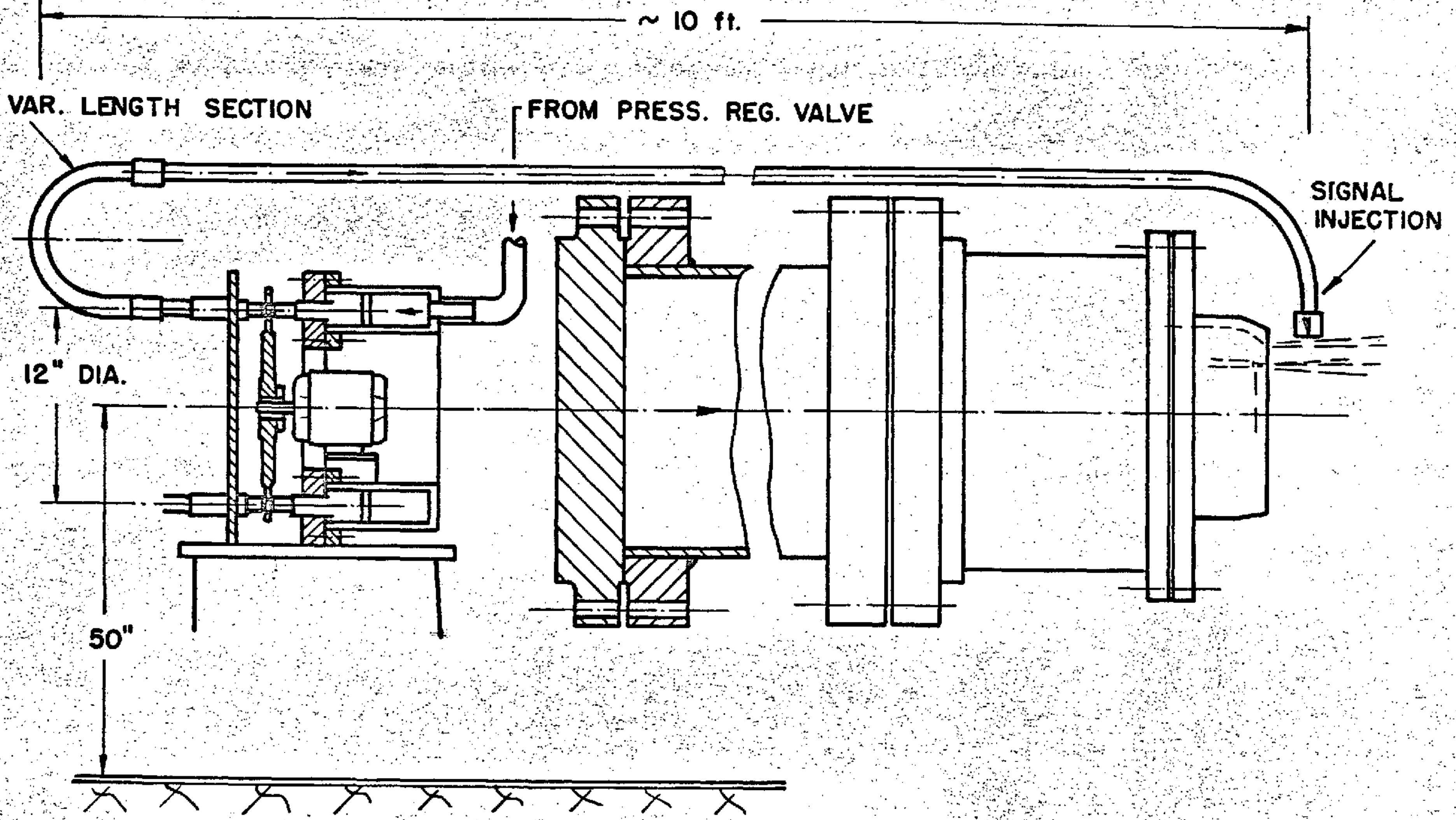


Fig. 7 Pneumatic noise signal generator and conduction to signal injection points

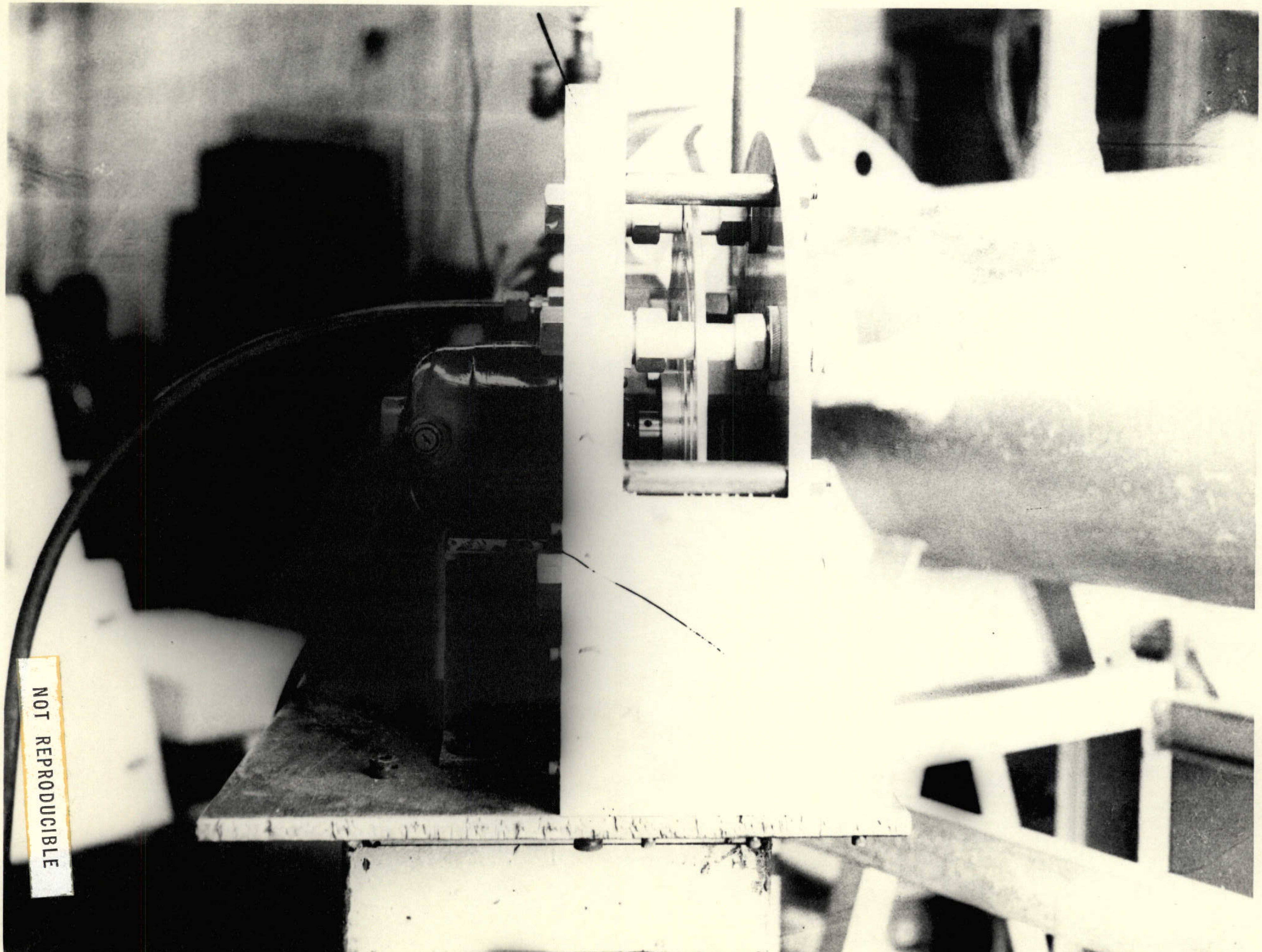


Fig. 8 Pneumatic noise signal generator

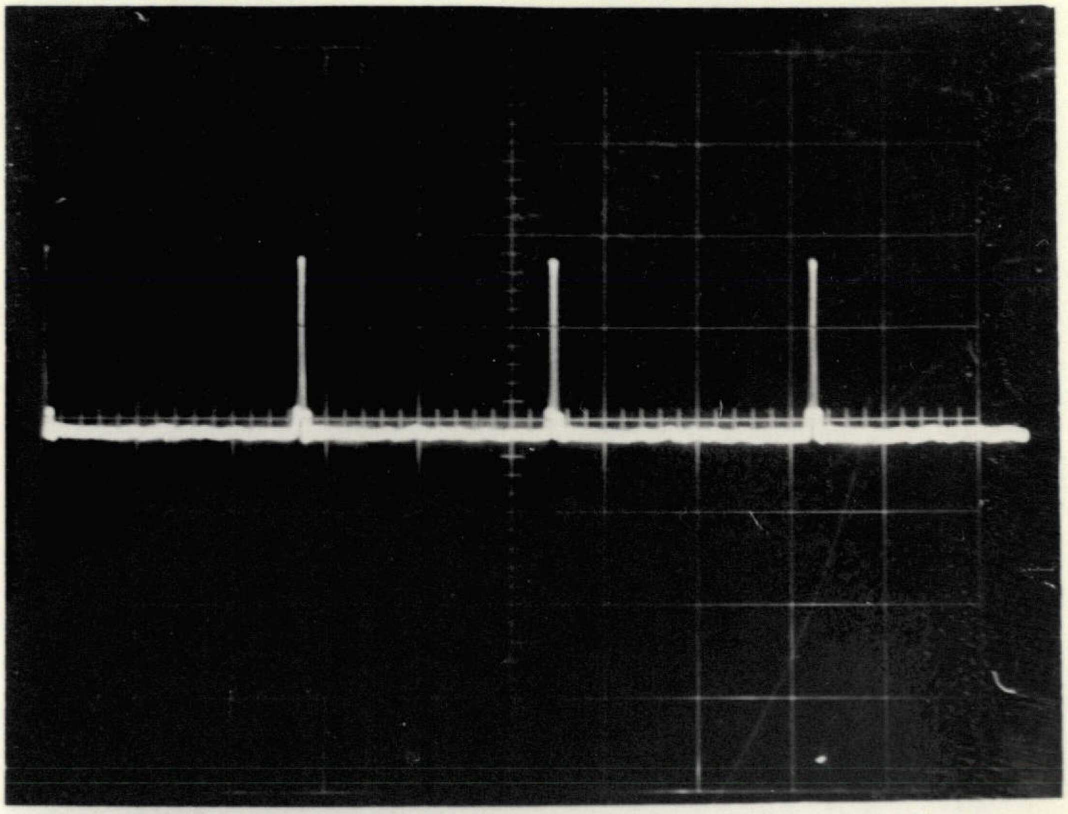


Fig. 9 Signal arriving to the regenerator after 10 ft. ~~pipe length in form of spikes (5KHz)~~

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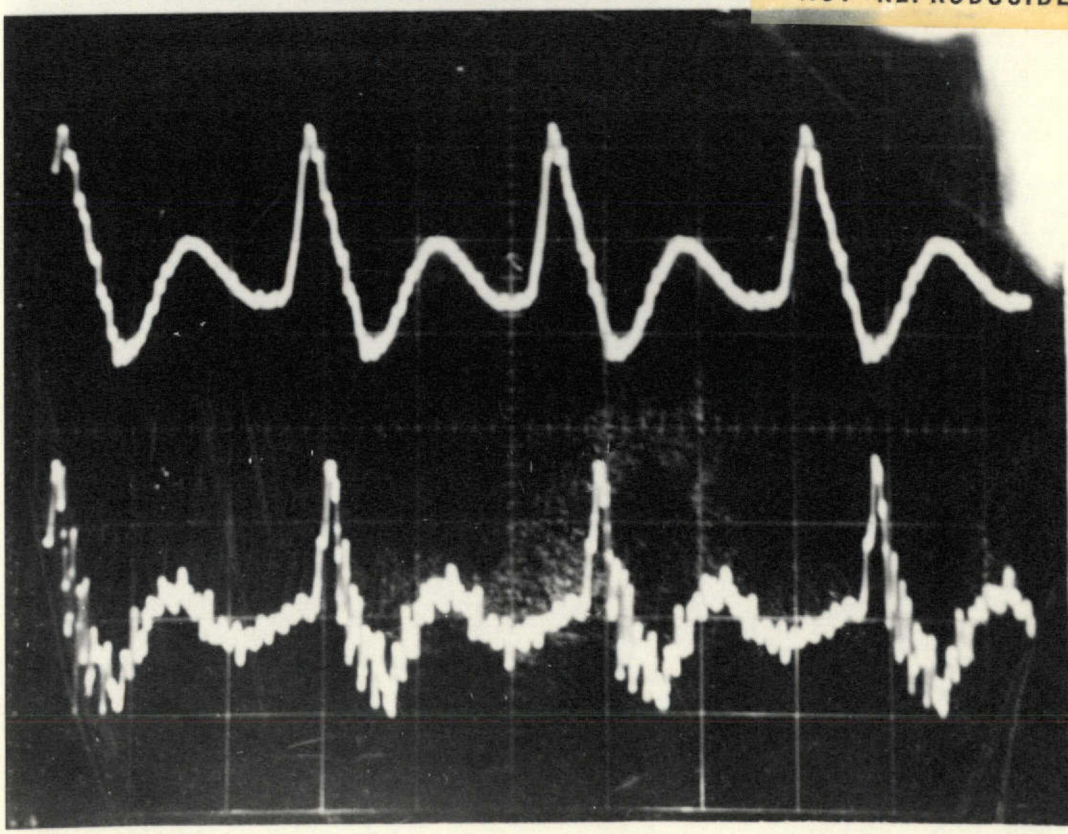


Fig. 10 Signal regenerated by Helmholtz resonator

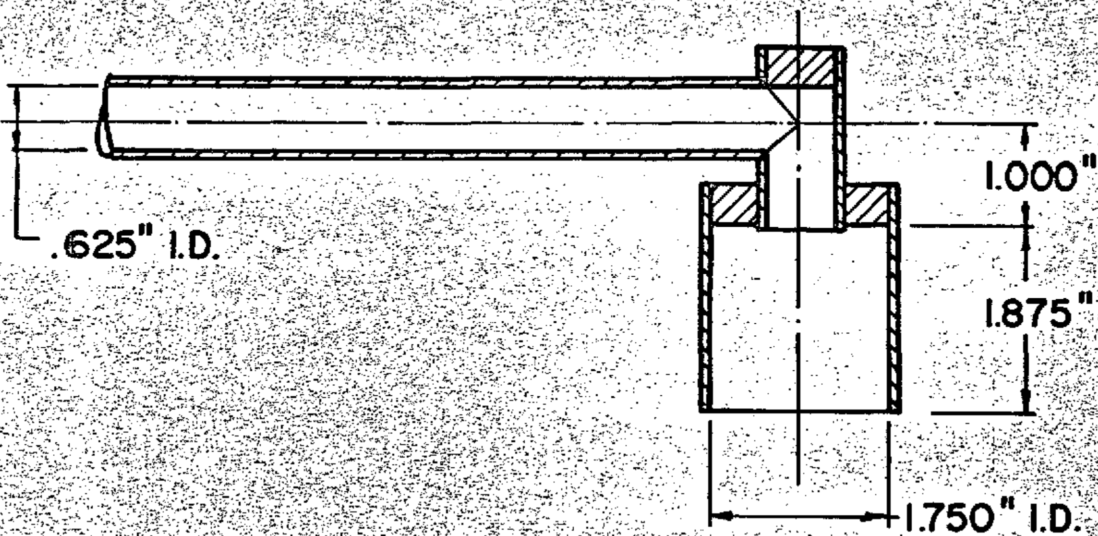


Fig. 11 Helmholtz resonator to regerate signal with small slope

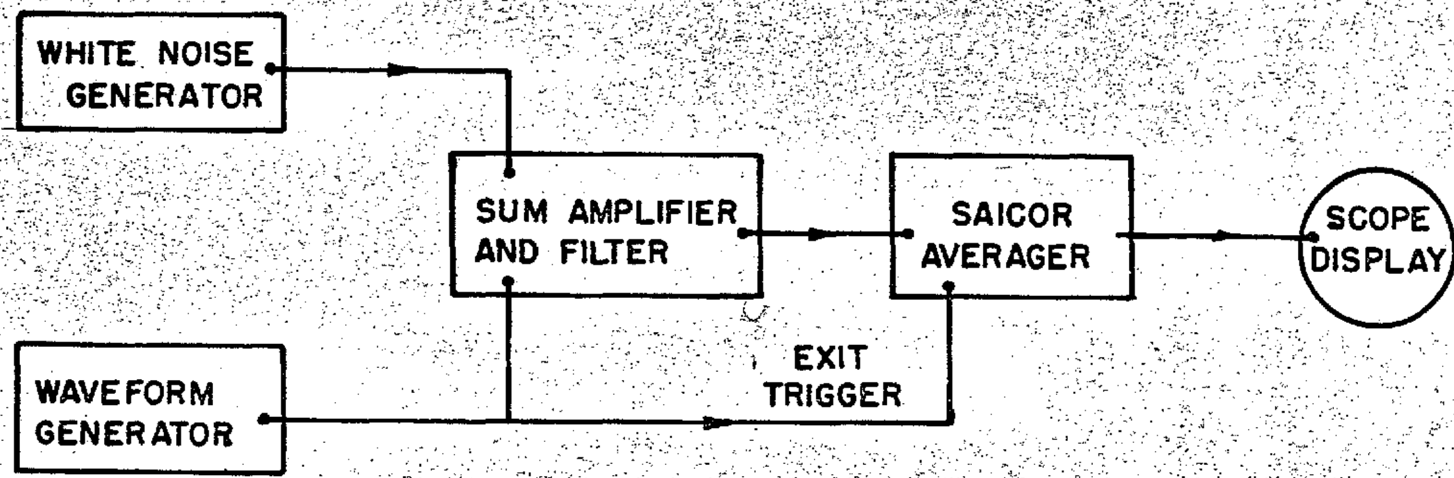
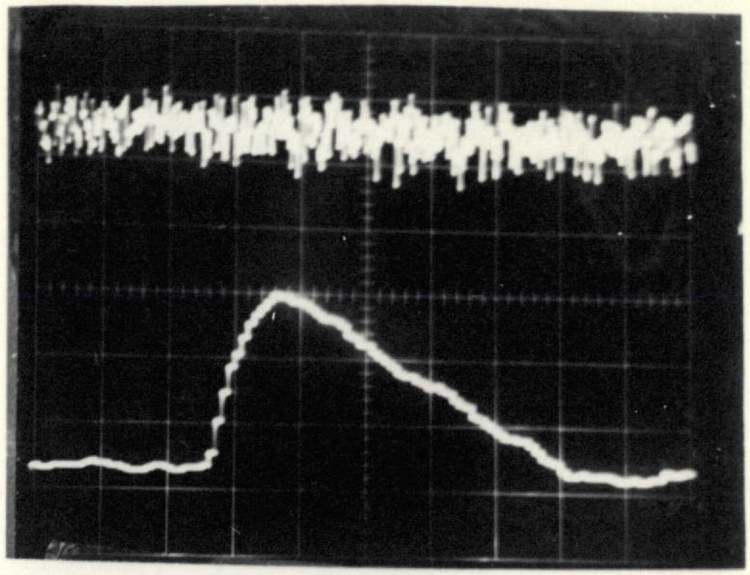


Fig. 12 Simulation of Signal noise mixing and separation to evaluate enhancing system characteristics

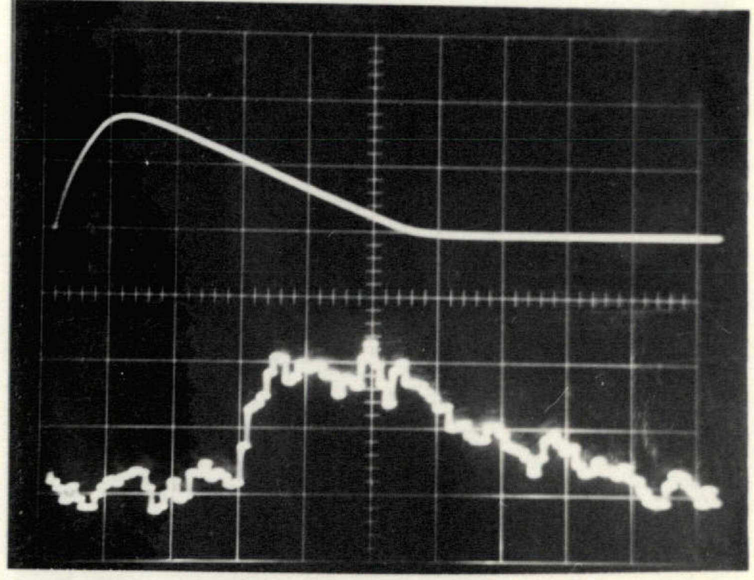
2a) Signal and noise mixed
Noise/Signal=64

2b) Signal separated with
more than 200K summations



1a) Signal injected

1b) Signal separated with
16 K summations N/S=64



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3a) Signal separated with
64 summations N/S=64

3b) Signal separated with
32 K summations N/S=64

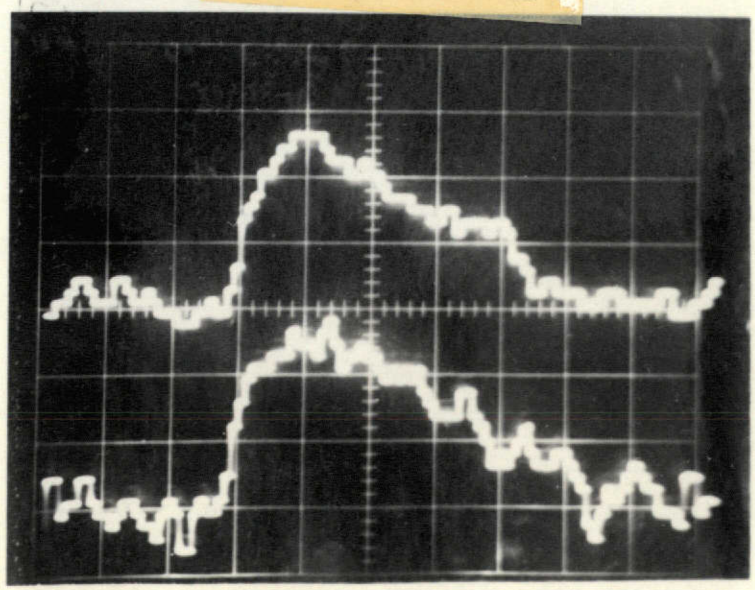

Fig. 13-1 Signal Enhancing

4a) N/S=32 Σ=16K

4b) N/S=16 Σ=16K

5a) N/S=8 Σ=16K

5b) N/S=8 Σ=8K

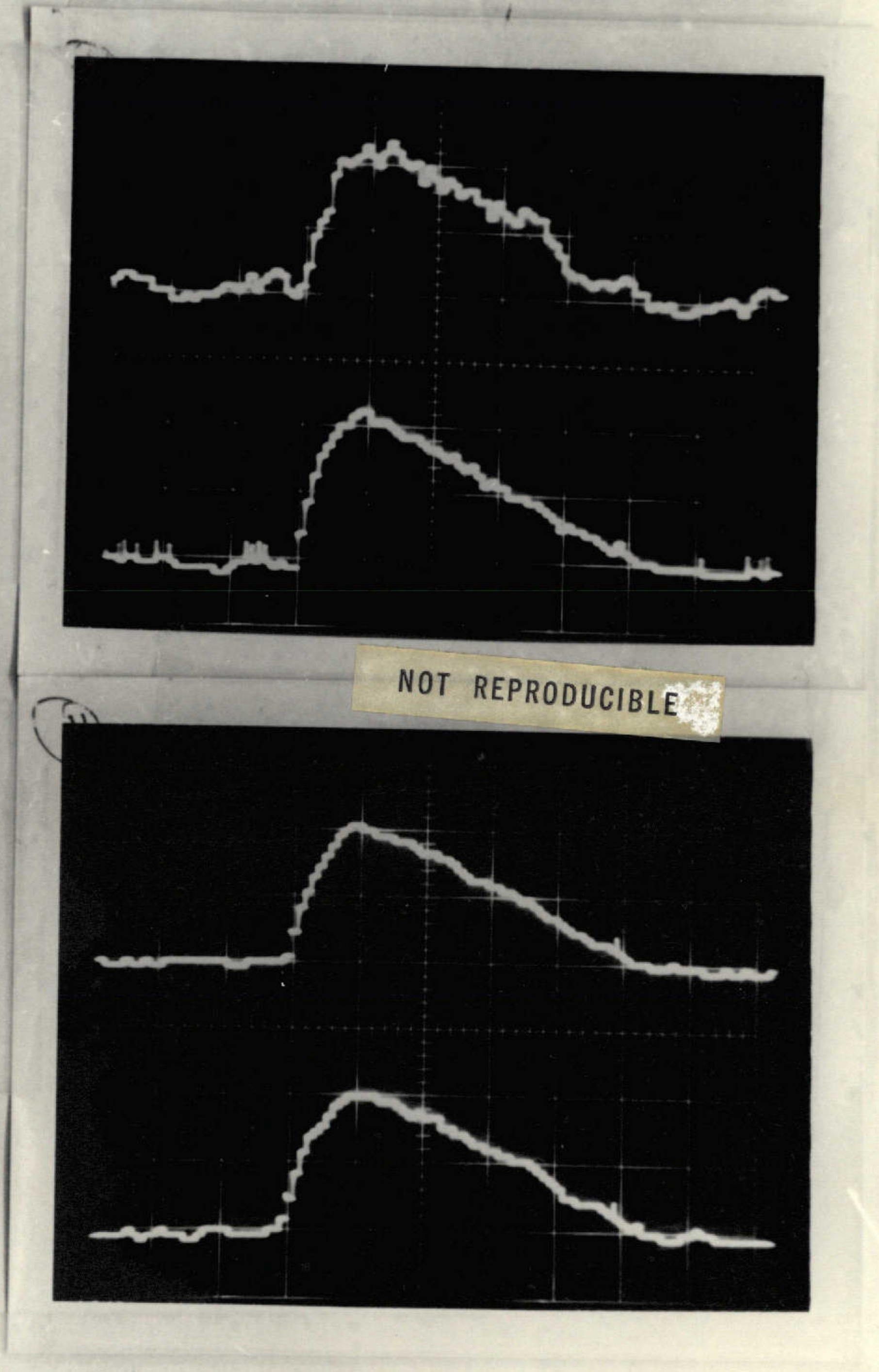

Fig. 13-2 Signal Enhancing